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Advances in understanding young high-mass stars using optical interferometry

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Abstract. The closest examples of high-mass star birth occurs in deeply embedded environments at kiloparsec distances. Although much progress has been made, an observationally validated picture of the dominant processes which allows the central hydrostatic object to grow in mass has yet to be established. The observational technique of optical interferometry has demonstrated its potential in the field of high-mass star formation by delivering a milli-arcsecond infrared view on the complex accretion environment. We provide an overview of the scientific results obtained with multi-aperture telescope arrays and briefly discuss future instruments and their anticipated impact on our understanding of massive young stellar objects.

1. Introduction

Optical interferometry (OI) decouples the single telescope diffraction limit from the angular resolution limit. This can be achieved by combining the light-beams coming from an array of telescopes in order to create interference fringes. OI as an astronomical observing technique has come of age during the first decade of this century. At the turn of the century, there were less than 100 refereed science papers that used OI data. This number grew exponentially to ~ 500 in the period between 2000 and 2011 (Ridgway et al. 2012). General user facilities like the Very Large Telescope Interferometer (Glindemann et al. 2004), the Keck Interferometer (Ragland et al. 2010), CHARA (ten Brummelaar et al. 2011) and IOTA (Traub et al. 1998) have made this development possible. For the first time, a clear window on astrophysics is provided with milliarcsecond resolution in the optical and infrared wavelength range. Such angular resolution translates to direct access to sub-AU stellar physics and probing the stellar surfaces of the largest stars in the sky. Additionally, the first OI synthesis images have provided new understanding of many challenging phenomena since 2007 (for a review, see Berger et al. 2012). Consequently, the technique has opened new horizons in stellar and AGN physics.

The field of high-mass star formation has been awarded with significant progress thanks to increasing sensitivity of infrared (IR) instruments and the exploitation of the IR wavelength region by satellites like ISO, Spitzer, and Herschel. New views have been obtained on outstanding questions regarding fragmentation and formation of massive molecular cores from Giant Molecular Clouds, radiative feedback during the main accretion phase, the physics of molecular flows and the kinematic feedback on the natal molecular clump, and the geometry of the accretion flow onto the young star (Zinnecker & York 2007; Beuther 2011). Many authors have noticed similarities between the ac-

cepted paradigm of (isolated) low-mass star formation and the evidence for disks, jets and outflows associated with young high-mass stars ($M_* > 8 M_\odot$). Yet, the required high accretion rates, the high mass-infall rates from the massive envelope, the feedback from the star, the high-momentum mass outflows and last but not least, the massive star multiplicity could, potentially, all spoil this similarity. These concepts become manifest on short timescales and in a deeply embedded environment. The closest high-mass SF regions are typically located at kpc distances requiring sub-arcsecond resolution in order to advance on these challenges. Such spatial resolution is what modern optical and (sub-)mm interferometers provide.

The application of OI to the field of massive star formation has been a relatively recent development (de Wit et al. 2007). The technical challenge of OI applied to the study of massive young stellar objects (MYSO) is to collect enough *optical and near-IR* photons in order to stabilize (in real-time!) the various telescopic and interferometric control loops. This poses challenges to applying the technique to young massive stars. MYSO are optically dark, near-IR faint and only in the mid-IR the sources become detectable. Added to this is the complication that not only the science target but in general the large majority of the neighbouring stars are buried in the natal cloud core and therefore relatively faint at optical and near-IR wavelengths. In case of the VLTI, the adaptive optics system MACAO, the fringe-track system FINITO, and the IR tip-tilt system IRIS work with optical or near-IR photons.

This brief review aims to fit the results obtained with OI into our growing understanding of the birth of individual high-mass stars. We give a compact overview of the advancements over the past years before detailing the contributions by OI.

2. Optical interferometry at the VLTI

The only interferometric array that has achieved scientifically validated OI-fringe data on MYSOs so far is the VLTI array, operated by ESO on Cerro Paranal. The VLTI is a versatile interferometric array that schematically consists of three basic elements: 4 *telescopes* that feed an interferometric *beam-combiner instrument* after the optical path length is equalized via a *delay-line carriage system*. The employed telescopes can either be the four 8.2m Unit Telescopes or the four mobile 1.8m Auxiliary Telescopes (see Hagenauer et al. 2008). The telescope platform on Paranal is equipped with 30 possible AT locations (“stations”) which are connected with the delay-line tunnels by underground light ducts. In operation mode, the VLTI offers ~ 9 stations which are subdivided into three distinct AT quadruplet configurations. The baseline lengths of the currently offered quadruplets range between 11 and 140 meters. Since 2005, ESO has offered to the community 2 single-feed, spectro-interferometric, instruments. AMBER operates in the near-IR. It combines 3 telescope beams delivering spectrally dispersed interferometric fringes for three spectral resolutions (Petrov et al. 2007). MIDI is a 2 telescope combiner and delivers fringes at two possible spectral resolutions in the N-band (Leihner et al. 2003). The combination of wavelength and baseline results in a resolution of $\lambda/2B = 1.6$ milli-arcsecond in K-band.

Spectro-interferometry is the technique which allows the combination of high spectral with spatial resolution. It is a powerful tool to perform spatially resolved kinematic studies of, for example, gaseous circumstellar disks (see e.g. Štefl et al. these proceedings). By means of fringe phase measurements, the VLTI data give access to photocentre displacement and asymmetries on angular scales of tens of micro-arcseconds

(e.g. Wheelwright et al. 2012b). For reference, the angular resolution of ALMA is 5 milli-arcsecond at the shortest wavelength (0.3 mm) and largest configuration (14.5 km), similar to the angular resolution offered by the VLTI. This complementarity is of interest to massive star formation studies in, for example, uniting hot accretion physics with the cold disk physics aiming for a complete picture of a massive star accretion disk. Last year, 2011, marked the 10th anniversary of the VLTI “first light” with a dedicated ESO science meeting. All presentations are available on the internet¹.

3. Boundary conditions of high-mass star formation

Star formation occurs in molecular clouds, but clearly not all molecular clouds produce high-mass stars. Clouds that do are a subset of the Infra-Red Dark Clouds (IRDCs, Egan et al. 1998; Kauffman & Pillai 2010; Peretto & Fuller 2010). These are cold and dusty filamentary interstellar structures with high column densities which renders them optically thick to the background mid-IR radiation field. These physical conditions are thought to be representative of the boundary conditions for the formation of high-mass molecular cores: the analogue of the low-mass starless cores. High-mass cores are envisaged to collapse without any significant fragmentation (i.e. mono-lithic), resulting in an individual high-mass star (McKee & Tan 2003). However, such high-mass cores have escaped unambiguous detection (e.g. Caselli 2011), although angular resolution and sensitivity in the mm wavelength regime may be responsible for the current non-detection (see Krumholz, these proceedings). On the other hand, a real absence of massive pre-stellar cores would imply that molecular cloud clumps fragment down to low-masses. How would such a scenario give rise to a stellar mass distribution extending up to high-mass stars? One idea envisages that the fragments’ motion through the molecular clump results in different (Bondi-Hoyle) accretion rates and high-mass objects would materialize because the progenitor fragment happened to accrete material from the densest clump regions (i.e. nominally the clump centre). A recent overview containing a detailed description of both models can be found in Bonnell & Smith (2011). For this review it suffices to state that this earliest, pre-stellar, phase of high-mass stars does not have any clear-cut observational counterpart, and are therefore observationally inaccessible. A large body of work is directed towards finding these objects with e.g. Herschel (Motte et al. 2010; Molinari et al. 2010) and ALMA will have a crucial role to play.

Nonetheless, somewhat more advanced phases in the high-mass star formation process within IRDCs are easily identifiable. Deeply buried by the molecular core material, a central object warms its immediate surroundings up to several 100s of degrees. The elevated temperatures are betrayed by molecular line transitions: a variety of chemical species, initially frozen onto the dust grains, sublime and are released into the IS medium. These species give rise to the typical “hot core” spectrum characterized by a plethora of (sub-)mm line transitions of different complex organic molecules (Cesaroni et al. 2005, 2010). Additionally, these early phases of a young high mass star are characterized by compact and bright mid-IR emission (Henning et al. 1990), bipolar, high-velocity CO emission (Snell et al. 1988; Beuther et al. 2002), shock released SiO emission (Jiménez-Serra et al. 2010), and water/methanol (6.7GHz) maser

¹http://www.eso.org/sci/meetings/2011/VLTI_2011/program.html

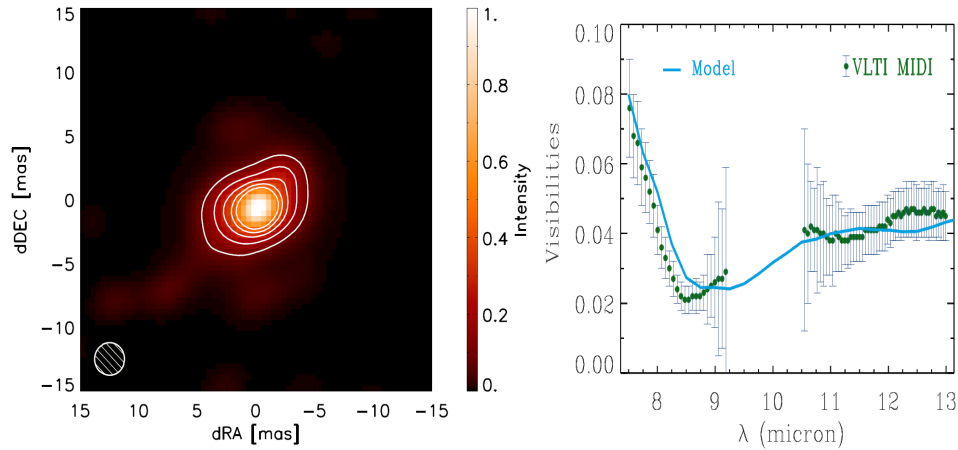


Figure 1. *Left:* AMBER OI synthesis image by Kraus et al. (2010) (Reprinted by permission from Macmillan Publishers Ltd: Nature 466, 2010) *Right:* Dispersed MIDI visibilities (with errorbars) and model (full line) which combines a gaseous accretion disk and dusty envelope (de Wit et al. 2011).

emission (e.g. Walsh et al. 1997). These are all hallmarks of young high-mass stars ($L_{\text{bol}} > 10^4 L_{\odot}$), and this embedded phase is generally identified as the massive YSO (Lumsden et al. 2002), accessible to detailed study.

4. Massive YSOs and accretion

One of the main questions in high-mass SF regards the accretion of mass by the central, embedded, star. MYSOs display a number of observational properties which are consistent with (very) high accretion rates, where careful estimates based on molecular outflows seem to indicate values up of $10^{-3} M_{\odot} \text{ yr}^{-1}$ (Beuther et al. 2002; Zhang 2005). The most recent accretion disk simulations show that high accretion rates can be sustained by means of very effective gravitational torques leading to non-axisymmetric distribution of the disk material (Kuiper et al. 2011). The presence of a disk significantly reduces the adverse effects of the radiation pressure on the infalling material by preferentially beaming photons into the polar direction (Krumholz et al. 2005). Until recently, direct observational evidence (i.e. a spatially resolved image) of an accretion disk around a young high-mass star was impossible because of the angular scales involved. The best evidence until recently was probably the 130 AU disk detected in mm continuum near a $\sim 10 M_{\odot}$ star (Shepherd et al. 2001). This situation changed radically with the creation of a VLTI interferometric synthesis image in the near-IR (Fig. 1). From AMBER visibilities and closure phase measurements supplemented with short spacing, NTT speckle images, Kraus et al. (2010) applied image reconstruction techniques to create a synthesis image of the MYSO IRAS +13481 ($\sim 20 M_{\odot}$) with a spatial resolution of 2.4 milli-arcseconds ($\sim 8.4 \text{ AU}$). This is the highest resolution MYSO image ever created to date. The image shows a structure with a smooth spatial profile that is centrally peaked. It strongly suggests a disk geometry for the continuum emitting material. This interpretation is re-inforced by the fact that the disk's orientation is perpendicular to that of a large-scale, bipolar, CO outflow. In addition, this outflow may be

driven by an accretion induced jet which is the main suspect of a parsec-scale collimated H_2 flow (Stecklum et al. 2010). (The $\text{Br}\gamma$ emission is scrutinized in sub milli-arcsecond detail by SINFONI integral field spectroscopy, see Stecklum et al. these proceedings.)

The reconstruction of a near-IR image at a resolution of 2.4 milli-arcsecond constitutes an important step forward in understanding the circumstellar environment of an accreting high-mass star, yet the interpretation of the OI synthesis image is not straightforward. The observed spatial distribution of the near-IR emission together with the source's SED are consistent with reprocessed stellar emission by a dusty disk+envelope system. In this particular model, the disk mass is the same as that of the central stellar source, i.e. $\sim 20 M_\odot$. The inner disk is located at a radius of 6.2 AU, which roughly corresponds to the dust sublimation radius. As a consequence, IRAS +13481 appears to comply with the well-known near-IR luminosity-size relation established for lower mass pre-main sequence stars (see e.g. Dullemond & Monnier 2010). If this interpretation is correct, a very attractive unifying scenario would emerge in which the AU-scale, near-IR emission of all accreting young stars is dominated by dust sublimation physics. Indeed, the AMBER synthesis image is found to be consistent with a warm, puffed up inner disk rim. However, confrontation with a $20 \mu\text{m}$ single-dish image proves the limitations of the particular envelope model (Wheelwright et al. 2012a), while observations on milli-arcsecond spatial scales provided by the VLTI-MIDI instrument also shows that a puffed-up dust sublimation rim as the origin for a large fraction of the near-IR photons has some trouble and may need revision (Boley et al. in prep.).

The OI technique offers the unique possibility to study the morphology of circumstellar disks around young high-mass stars at wavelengths longer than K -band. At the near-IR wavelengths, scattering and envelope extinction hamper the direct detection of disk light. At longer, mid-IR wavelengths, the contribution by the warm envelope dust ramps up, slowly drowning disk photons. There is a 'sweet spot' in terms of wavelength between K and N -band where the circumstellar disk is prominent and may dominate the total light. Interferometry of MYSOs using MIDI in the N -band probing ~ 100 AU clearly demonstrates the absence of rotational symmetry in a couple of case studies. Subsequent radiative transfer modelling suggests that the geometry of the N -band emission is consistent with that of an equatorially flattened structure (Follert et al. 2010; Grellmann et al. 2011). The power of interferometry is that the various contributions to the correlated fluxes is the flux weighed by the size; at milli-arcsecond resolution the envelope emission is almost resolved out, and any contribution by an unresolved structure e.g. a disk will become evident. Such an interpretation of MIDI observations of the well-known embedded young massive star AFGL 2136 is presented by de Wit et al. (2011). An increase in visibilities at the blue edge of the N -band (see Fig. 1) is consistent with the presence of an alpha-type accretion disk located within (< 170 AU) the dusty envelope, accreting at a rate of $3 \times 10^{-3} M_\odot \text{yr}^{-1}$. A remarkable detail, imposed by N -band, short-spacing Keck data (Monnier et al. 2009), is that the rim of the dust envelope is found at about 7 times the formal dust sublimation radius. The central dust-free zone could have been evacuated by the ionized stellar wind, seen by Menten & van der Tak (2004).

It is clear that both in-depth OI studies to clarify the accretion physics and survey-type of OI work to probe the frequency of disks and their properties are badly needed to provide a full picture of MYSOs as function of e.g. luminosity or age.

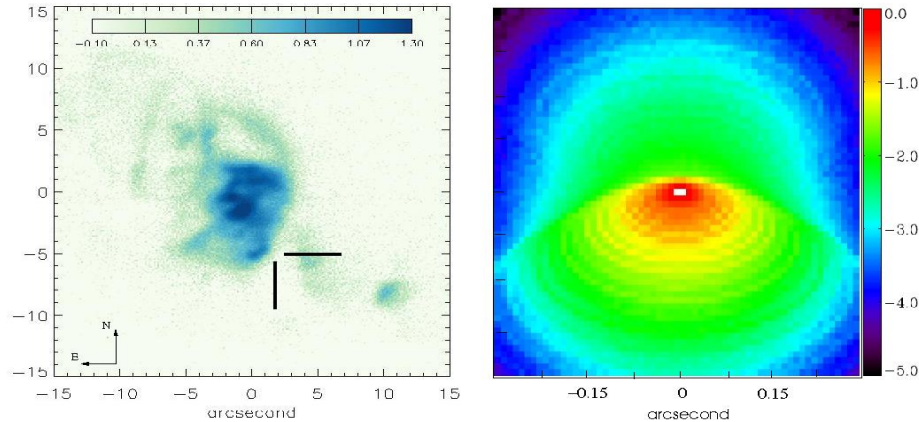


Figure 2. *Left:* Large scale thermal cavity wall emission at $24.5\mu\text{m}$ in Cep A HW2. The two bars indicate the phase centre (i.e. the central source) of the VLA 7mm map by Jiménez-Serra et al. (2007), adapted from de Wit et al. (2009). *Right:* RT model image at $12.5\mu\text{m}$ of a MYSO envelope with evacuated cavities which fits MIDI visibilities of W33A. The image is $0.6''$ on each side (de Wit et al. 2010).

5. Observational consequences of disk accretion

The presence of small-scale disks around MYSOs is inferred from the upper limits of high-precision spectro-astrometric signals of near-IR CO bandhead emission (Wheelwright et al. 2010). Performing OI and spectrally resolving near-IR spectral features like the CO-bandhead or the hydrogen recombination lines of MYSOs is currently at the sensitivity limit of the VLTI. It can be expected to shed light on the geometry and origin of the warm molecular material and the hot gas in the near future. It is important to keep in mind that the envelopes of MYSOs can be optically thick even in the mid-IR (e.g. Fig. 2) and the ability to peer deep into the inner regions depends critically on the inclination and the evolutionary stage. Radio emission is thus highly suitable to study the most extincted regions. Unfortunately, MYSOs display little ionized emission despite their high L_{bol} . Any weak radio emission is found to be compact (~ 100 AU, van der Tak & Menten 2005). The nature of this emission is under debate but it could be connected to the outflow activity. For example, Guzmán et al. (2010) report the discovery of a string of radio blobs emanating from either side of a $7 \cdot 10^4 L_{\odot}$ source. A highly collimated radio jet is present in Cep A HW2 (Torrelles et al. 1996) displaying velocities of 500 km s^{-1} (Curiel et al. (2006)). Spectro-astrometry of the MYSO W33A, probing photo-centre shifts of $\sim 100\mu\text{-arcsecond}$, already shows a bipolar geometry for the Br γ emission with a position angle that coincides with the arcminute molecular outflow (Davies et al. 2010).

The ubiquity of CO outflows in MSF regions and their scaled up properties compared to those of less luminous systems is indicative of a common mechanism (Shepherd et al 1998; Beuther et al. 2002). Varricatt et al. (2010) probe the incidence of linear, shock excited molecular H_2 emission at $2.12\mu\text{m}$ associated with MYSOs. The authors address the question whether jets are the driving mechanism of CO outflows (Torrelles et al. 2011) rather than the wind of the underlying star. Approximately 50% exhibit H_2 emission features along the molecular outflow direction in a sample of 50 massive SF regions. They also find that the H_2 emission is absent or comparatively

weak towards UCH II regions. This is in line with the idea that high mass infall rates quench the formation of an H II region (Walmsley 1995); the absence of radio emission is a proxy for ongoing accretion. Infall rates determined from sub-mm studies of rotating motion on scales of > 1000 AU indicate infall rates even higher than those determined from molecular outflows: $10^{-3} - 10^{-2} \text{ M}_{\odot} \text{ yr}^{-1}$ (Beltran et al. 2011).

Sustained high accretion rates (possibly episodic as deduced from H_2 flow morphology) induce a considerable effect on the stellar structure of the growing, quasi-hydrostatic, stellar core. With time, the Kelvin-Helmholtz timescale will decrease non-linearly and becomes shorter than the star's evolutionary timescale. The stellar interior will effectively transport radiation outward because of the decreasing Kramer's opacity, resulting in a swelling of the protostar (Hosokawa, York & Omukai 2010). OI with the MIDI instrument has provided some preliminary evidence that a swollen star is present in the source M8E-IR (Linz et al. 2009). The predicted stellar radius of these rapidly accreting object ($\sim 100 R_{\odot}$) will strongly reduce the accretion luminosity associated with the disk ($L_{\text{acc}} \propto R_*^{-1}$) and thus the observed bolometric luminosity should be dominated by emission from the central object. Importantly, the swollen star mechanism constitutes a noteworthy alternative for the faint, compact radio emission of MYSOs. Rather than the ionized emission being quenched by high accretion rates, the photosphere of the central object is cool and does not emit any ionizing radiation. The observed compact emission could be caused by shocks generated by the interaction of the collimated wind with the surrounding envelope material and cavity walls (e.g. Parkin et al. 2009).

6. Milli-arcsecond observation of the outflow cavity

Spherical geometries for the MYSO envelope generally fail to reproduce the observed fluxes at wavelengths shortward of $20 \mu\text{m}$ (e.g. Mueller et al. 2002; de Wit et al. 2009). Such models are unable to predict correctly the depth of the $10 \mu\text{m}$ absorption feature and the overall shape of the (sub-)mm SED. Attempts to shed light on this issue by means of spatially resolved mid-IR imaging failed when using 4m apertures (e.g. Mottram et al. 2007). Observations with 8m class telescopes have been able to spatially resolve the mid-IR emission for a couple of case studies. They revealed that the mid-IR emission is aligned with the larger scale CO molecular outflows (De Buizer 2006, 2007). Segment tilting interferometry at N-band with the 10m Keck also resolves the MYSO envelope demonstrating complicated, often bipolar, structures (Monnier et al. 2009). These findings associate the mid-IR emission of massive YSOs with outflow cavities, or, more specifically, with parts of the dense, dusty envelope close to the evacuated cavities which experience near-direct irradiation by the hot central parts.

N-band OI performed with MIDI on unresolved MYSO sources spatially resolves the emission on scales of tens of milli-arcseconds or ~ 100 AU. Radiative transfer modelling allowed the conclusion that the emission is consistent with thermal envelope emission (de Wit et al. 2007; Linz et al. 2009). In particular, a detailed modelling is presented in de Wit et al. (2010) for the luminous MYSO W33A. The authors manage to model the MIDI interferometry, near-IR scattered light images and the SED simultaneously. A dust geometry was chosen which includes a rotating, infalling envelope with dust-devoid, polar paraboloids representing the cavities carved by the jet/outflow. An excellent fit was found to all observables and which, moreover reproduces the observed 350 micron morphology (van der Tak et al. 2000) quite accurately. Close inspection of the envelope temperature distribution clearly reveals that the N-band emission is com-

pletely dominated by warm dust in the cavity walls on 100 AU scales, directly irradiated by the central star (see Fig. 2). The accretion rate of a circumstellar α -type disk would need to be more than $10^{-3} M_{\odot} \text{ yr}^{-1}$ for it to exceed the cavity wall emission.

The success of this model was recently extended in Wheelwright et al. (2012a). The authors successfully apply this model to simultaneously recreate the resolved Q-band emission and SEDs for a large MYSO sample. They simply vary the cavity opening angle, inclination and the total amount of dust of the W33A model. The mere fact that this approach works quite well argues against a large effect, if any by a circumstellar disk on the Q-band emission. This conclusion can also be inferred from an accretion disk SED, since it peaks at wavelengths shorter than $20 \mu\text{m}$. Furthermore, the envelope contains much more cool material than does any reasonable accretion disk, whose sizes for MYSOs are estimated to be less than 500 AU (see e.g. Patel et al. 2005; Hoare 2006; Reid et al. 2007; Jiménez-Serra et al. 2007; de Wit et al. 2011; Goddi et al. 2011). It is reasonable to expect that dust emission from the envelope (i.e. the cavity walls) dominates the continuum SED at wavelengths longward of the N-band. This is in agreement with the finding that the observed extension of the Q-band flux can be modelled as cavity wall emission. Resolved imaging and especially OI thus deliver excellent possibilities to probe the base of the outflow and explore in detail the mass loss processes during the accretion phase.

7. Summary and outlook

Observational and numerical evidence is accumulating that accretion disks can build stars up to $25 M_{\odot}$. Although no observational evidence exists that stars of higher masses follow the same channel, numerical simulations clearly allow for the accretion disk mediated formation of stars of $100 M_{\odot}$ and more. The disk density distribution and the high mass infall rates will lead to fragmentation and collapse of secondary and multiple objects (Krumholz et al. 2009) and the disk is expected to remain relatively small (Kratter et al. 2008). OI has provided the first direct evidence for a disk near a high-mass star at a spatial resolution of 8 AU in the near-IR. The increased sensitivity of the VLTI, implementation of new sub-systems and observing modes, and sophisticated post-processing algorithms will potentially make spectrally resolved studies of ionized gas and warm molecular emission possible on similar spatial scales.

The warm dust located close to the outflow cavities is responsible for a large fraction of the mid-IR emission emanating from structures on 100 AU scales. In hydrodynamic simulations of MYSOs, the stellar wind momentum is not sufficient to break out of the infalling envelope by an order of magnitude or more and would lead to Rayleigh-Taylor instabilities resulting in the collapse of the cavities (Krumholz et al. 2005; see also Kuiper et al 2012). Seifried et al. (2012) confirm the appearance of a fast jet generated by a protostellar disk, but whether a fast jet is generated or a slow wide-angle outflow depends critically on the magnetic field strength. Tracing the jet structure gives a unique insight into the mass accretion process itself (e.g. Ellerbroek et al. these proceedings). A 3D magnetic field morphology of the disk-jet system Cep A HW2 could be reconstructed via maser polarization measurement using VLBI (Vlemmings et al. 2010) demonstrating that the magnetic field may play a crucial role in the formation of a MYSO jet (Carrasco-González et al. 2010). We have detailed how OI delivers complementary spatial information in order to probe these various ideas and to advance on our understanding of the accretion/outflow mechanism in MYSOs.

The coming decade will see the VLTI as the only large aperture interferometric array. The second generation VLTI instruments will offer more sensitive and more efficient interferometric observations with Gravity and MATISSE being both 4-beam combining instruments. Especially MATISSE (first light 2015) offers a strong potential for permanent breakthroughs in our understanding of the formation of individual high-mass stars. This instrument will open up the wavelengths between K and N -band for OI, perfectly fitting for detailed studies of MYSO accretion physics.

Acknowledgments. I would like to thank the organization who provided me with the opportunity of presenting these results. Furthermore, I am grateful to all collaborators who have contributed to our common efforts to understand MYSOs. This manuscript was improved by the constructive comments supplied by R.D. Oudmaijer, B. Stecklum, J.S. Vink and H. Wheelwright.

Questions:

C. Martayan: There are $25\text{--}30M_{\odot}$ objects in your presentation. How did you do these estimates? What should be the resulting stellar masses of these objects?

W.J. de Wit: The mass is a direct conversion from the L_{bol} and ZAMS values. MYSOs with higher masses are not known. Indeed there is evidence that for the inferred \dot{M}_{acc} the hydrostatic object reaches the ZAMS at $\sim 30 M_{\odot}$ and will ionize its surroundings (see e.g. Davies et al. 2011).

J. Bjorkman: How well can you constrain the cavity opening angle from the N-band visibilities?

W.J. de Wit: Not at all. That's why we model the near-IR scattering nebula in case of W33A for example in order to obtain a handle on the outflow opening angle.

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